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The Status of Generation IV Sodium-Cooled Fast Reactor Technology Development and its Future Project

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Abstract

Fast Breeder Reactors drastically improve uranium resource utilization efficiency to realize thousands of years of nuclear energy usage, by means of building up a nuclear fuel recycling system (FBR cycle). FBRs can also transmute extracted minor actinides. Recently, new worldwide concerns are focused on counter measures against long-term energy security and global environmental problems due to developments of the emerging countries, leading to new attentions on the FBR cycle. This paper provides the status of sodium-cooled fast reactor technology development and its future prospects.

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Keywords: Generation IV; Sodium-Cooled Fast Reactor; Development Target; FaCT Project; Monju

1. Introduction

There are several diverse requirements for the future energy system as shown in Fig.1. It is our prime duty to cope with the significant requirements:

- Preservation of the global environment reducing wastes and release of detrimental and green-effect materials, and
- Establishment of the sustainable energy supply, avoiding resource exhaustion, with robust preparedness to the increasing demand in the developing countries and flexibility to uncertainty and change in growth rate in possible transitory phase to come.

From the global viewpoint, the energy system should function as a leading mechanism to achieve the transition from the current consumption-driven growth towards the environmentally harmonized and sustainable growth.

In this context, if the nuclear energy be accepted widely in the future society, it must give the clear perspective to these worldwide issues with technological background, and thereby play a major role in promoting the transition. In other words, the social worth of the nuclear energy significantly depends on how to innovate the technology towards this direction, in addition to enhancing safety and economic competitiveness

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It should be emphasized that nuclear technology has essentially inherent potential to accommodate "resource saving and little waste by recycling" principle and that the potential is most realized by the effective use of neutron generated and by thorough recycling of materials charged in the system. Fast Breeder Reactors (referred to as "FBR" hereafter) embody such principle, namely they drastically improve uranium resource utilization efficiency to realize thousands of years of nuclear energy usage, by means of building up a nuclear fuel recycling system (FBR cycle). FBRs can also transmute extracted minor actinides (MAs), which are currently vitrified with (the other) fission products as high level radioactive wastes.

Recently, new worldwide concerns are focused on counter measures against long-term energy security and global environmental problems due to development of the emerging countries, leading to new attentions on the FBR cycle.

This paper provides the status of Sodium-Cooled Fast Reactor (referred to as "SFR" hereafter) technology development and its future project.

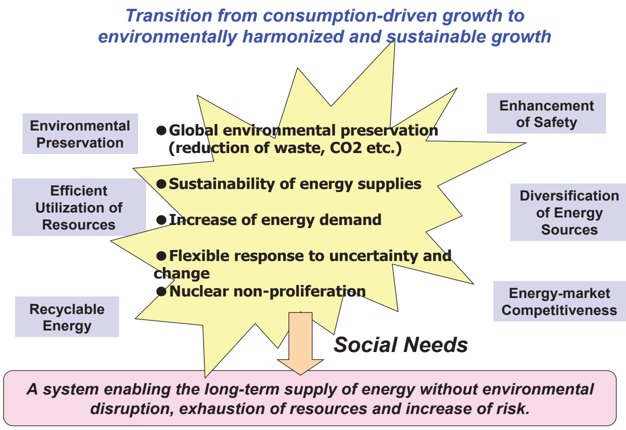


Fig.1 Development Target and Strategy for FR

2. Development Targets

Within the international collaboration in the framework of Generation IV International Forum (referred to as "GIF" hereafter), GIF firstly set the five development targets in order to cope with the diverse future needs. These are ensuring safety, reduction of environmental burden, economic competitiveness, efficient utilization of resources, and enhancement of nuclear non-proliferation. The development targets(1) for the Generation IV SFR are summarized as follows:

- Safety assurance

The safety design approach for the SFR places the highest priority on preventing the occurrence and evolution of abnormal conditions based on the concept of Defense in Depth. A safety level equivalent to or better than GenIII light-water reactor cycle systems should be achieved.

Passive safety functions should possibly be added or enhanced, and regarding the reactor, measures should be taken for the prevention of any hypothetical core disruption and exclude energetic sequences due to nuclear excursion, in order to ensure that the impact of such a hypothetical accident is confined within the boundary of the reactor vessel or the containment vessel.
The goal of the implementation of these measures is to render the risk of installing the SFR cycle system sufficiently small compared with other risks already existing in society.

- Economic competitiveness

For the commercialization of an SFR system, it is important to achieve a level of economic competitiveness that enables the system installation in accordance with market principles. For this purpose, an important goal should be to ensure enough competitiveness in terms of energy cost (unit cost of power generation) compared with the competing energy sources in the future.

- Reduction in environmental burden

With the excellent neutron economy characteristics of the SFR, there is a possibility of achieving further reductions in the exposure dose and risks associated with geological disposal, which are already at safe levels, by utilizing the transuranic (TRU) burning characteristics along with implementation of separation and transmutation methods. To this end, the development is advisable for the separation of nuclear transmutation technologies of long-life nuclides (TRU and LLFP (Long-life fission products)) generated by light-water reactors and fast reactors, that would allow the utilization of the full advantages of the closed fuel cycle of the SFR system.

Efforts should also be made for achieving reductions in the amount of waste generated from the operations and maintenance and the decommissioning of system facilities, and the amount of waste migrating to the environment.

- Efficient utilization of resources

The capacity for efficient burning of TRU materials, including degraded plutonium, and the excellent neutron economy are some of the advantages of the SFR, which enable the utilization of nuclear energy as a sustainable energy source over a very long time period of more than 1,000 years. Accordingly, the effective utilization of uranium resources includes the recycling of TRU.

The current outlook is that long-term demand for energy will keep increasing on a global scale, but because there is an element of uncertainty in any projection regarding energy supply and demand, an SFR system should possess the flexibility to adapt to changing energy needs by adjusting its actinide management capability (from net consumption to net generation of fissile material).

- Resistance to nuclear proliferation and enhanced physical protection

Among the technical features that contribute to the proliferation resistance of the SFR are the characteristics of the recycling process, which include the presence of minor actinides (MA) and highly radioactive (β, γ) fission products (FP) in the recycled fuel, rather than the separation of plutonium. This results in lowering the chemical purity and the fissile fraction of Pu, and in an increase in the surface dose rate of the recycled product. These features enhance the difficulty of accessing the nuclear materials in the fuel cycle and lower their attractiveness, since separated plutonium does not exist in its pure state in any of the system's processes.

Regarding the organizational aspects, it is necessary to implement nuclear safeguards (IAEA safeguards agreements) and to always maintain an accurate material inventory through the utilization of advanced technologies. An advanced system and facility design that allows for the integration of the safeguards and physical protection systems will ensure the implementation of effective accountancy, monitoring and protection measures. It is also necessary to maintain transparency and openness in terms of information in the relationships with external organizations.

3. System definition of Generation IV SFR

The three options, loop-type, pool-type and modular-type systems, are under consideration in GIF[(1)]:

- A large size (600 to 1500 MWe) loop-type sodium-cooled reactor with mixed uranium-plutonium oxide fuel, supported by a fuel cycle based upon advanced aqueous processing at a central location serving a number of reactors. [(2), (3)]
- A medium or large size (600 to 1500 MWe) pool-type systemalso supported by a fuel cycle. [(4),]
- A small size (50 to 150 MWe) modular-type sodium-cooled reactor with uranium-plutonium-minor-actinide-zirconium metal alloy fuel, supported by a fuel cycle based on pyrometallurgical processing in facilities integrated with the reactor. [(5)]

Hereafter, technology development and future prospect for SFR are described by referring the activities for FBR commercialization in Japan.

4. FBR commercialization in Japan

The "Framework of Nuclear Energy Policy" formulated by Japan Atomic Energy Commission in October 2005 states that the deployment for commercial utilization of FBRs from around 2050 is one of a guideline for promotion of nuclear power generation in the future. In March 2006, the Council for Science and Technology Policy (CSTP) of the cabinet office selected an FBR cycle technology as one of the key technologies of national importance in the third-term "Science and Technology Basic Plan." This means that an FBR cycle technology was reorganized as essential technology to be invested intensively in a large-scale national project during the period of the basic plan. After this, the Nuclear Energy Subcommittee of the Ministry of Economy, Trade and Industry compiled the "Nuclear Energy National Plan" where early commercialization of the FBR cycle is emphasized as one of fundamental policies. The demonstration reactor project is firstly indicated in the national plan officially with the start-up target around 2025.

The basic scenario toward commercialization of FBR in Japan is shown in Fig.2 with the history of FBR development.

- Resume the operation of Prototype FBR Monju. Monju has already restarted commissioning on May 2010.
- Around 2015, present an appropriate concept of the commercialized FBR cycle and an R&D plan until commercialization.
- Aim for the start of demonstration FBR operation and other related fuel facilities by around 2025.
- Start introducing commercial FBRs before 2050.

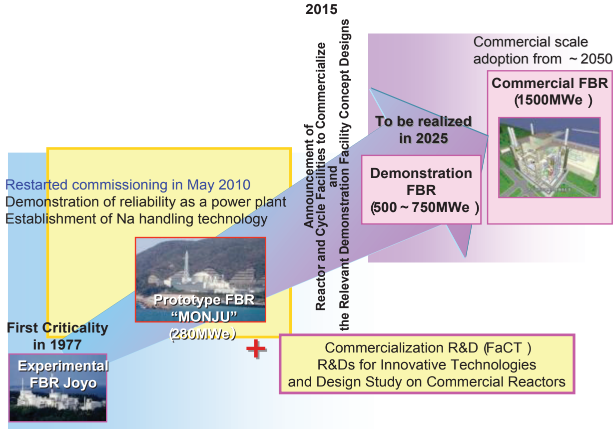


Fig.2 Fast Reactor Commercialization Strategy in Japan

5. R&D Program using Monju

Monju re-started on May 2010 after fourteen years cease.

Monju has, as the Japanese prototype reactor for the purpose of FBR commercialization, an important mission to provide indispensable technical information for design, operation, maintenance and demonstration of commercialized FBRs, implying that the demonstration and commercialized FBRs are on the extension of the Monju plant concept. At the moment in Japan, Japan Atomic Energy Agency is conducting a series of R&Ds toward FBR commercialization titled "Fast Reactor Cycle Technology Development" project (abbreviated as "FaCT" project), with the main target concept conforming to development goal for commercialization, which consists of feasible technical elements: "SFR", "advanced aqueous reprocessing" and "simplified pellet fuel fabrication".

The "Framework for Nuclear Energy Policy" by Japan Atomic Energy Commission mentions Monju as "Specifically, the operation of Monju, the core of the place for its research and development, should be resumed at the earliest possible time, and the priority should be placed on achieving the initial goals of demonstrating reliability as an operational power plant and establishing sodium handling technology, hopefully, within ten years or so. After that, (snip) we expect Monju to be utilized as a location for research and development activities toward commercialization of FBR (snip) Since international cooperation is important for these activities, it is necessary to develop Monju and its peripheral facilities as the center of international research and development cooperation, to implement research and development open to both domestic and foreign entities, and to demonstrate the achievements to both Japan and outside world."

In accord with these statements, Monju has plans for design technology verification of reactor core and elevated temperature sodium components for SFRs to lead to ensuring reliability of adopted technologies in the FaCT project, and for establishing plant technologies based on field experiences of operation, maintenance and repair of a real plant as shown in Fig.3.

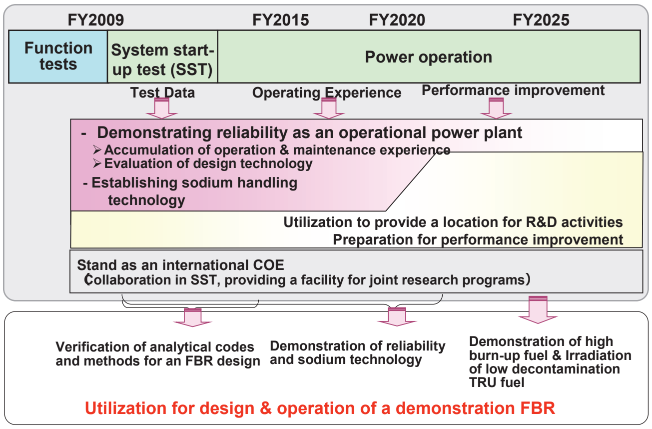


Fig.3 R&D Program using Monju

Expectation on Monju is thought to be significant because the other operable FBR prototype reactor in the Western countries, i.e. Phenix of France stopped in 2009.

Therefore the following three missions are given to Monju and are being fulfilled:

Firstly, "acquisition of prototype plant data" for obtaining operation and maintenance/repair information from a power plant, to be important for FBR development; Operational data obtained through System Start-up Test and operation in Monju verifies adequacy of the design technology employed for the system of Monju as well as its individual equipments (Reliability Demonstration as a Power Plant). Through operational experience in Monju, sodium handling technologies including sodium quality control, inspection, are established and common design methodology for commercialization is validated (Establishment of Sodium Handling Technology through Operational Experience). For example, reactor physics data obtained in the System Start-up Test in 2010 have been analyzed by the method developed in JAEA. Results of the calculation show that its accuracy is high enough to be required for FBR Commercialization as shown in Fig.4.

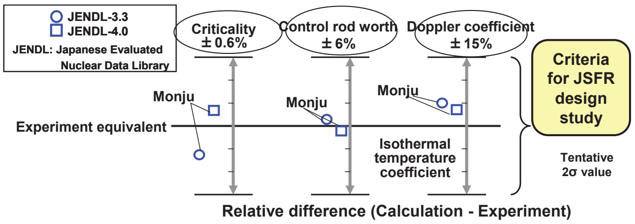
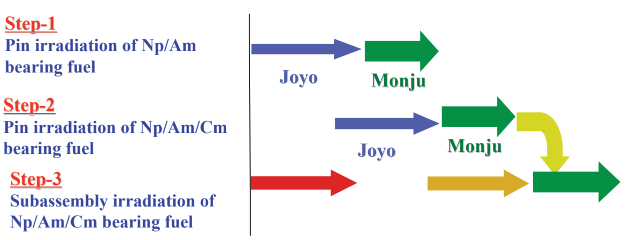


Fig.4 Results of Core Performance Tests in Monju

Secondly, "irradiation tests" to acquire FBR fuel and material irradiation data which are critical for every country having FBR development programs; The reactor core and fuel is to be demonstrated making use of capabilities of high irradiation and large subassembly irradiation in Monju (Utilization to provide a location for R&D activities). For example, as shown in Fig.5, Monju and Joyo are utilized for the irradiation as collaboration of GACID (Global Actinide International Demonstration) project in the framework of GIF to demonstrate the integrity of Minor-Actinide bearing fuel which is a major candidate fuel for commercial FBRs.



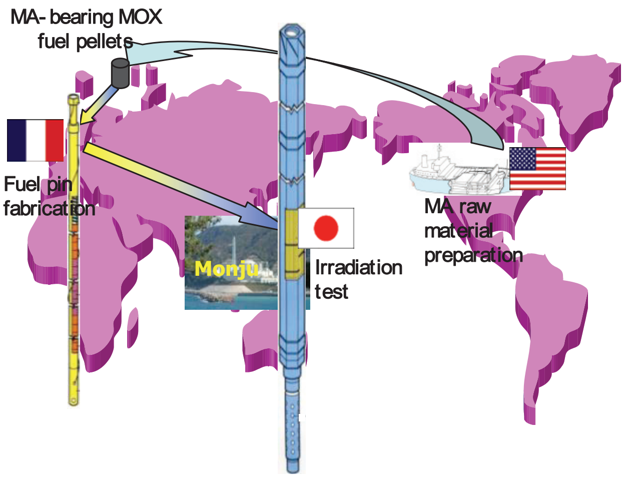


Fig.5 Global Actinide Cycle International Demonstration Project

Thirdly, “education and training” critical for upbringing FBR engineers and researchers in emerging countries to launch FBR developments and in advanced countries to accelerate FBR developments after past temporal slowdown.

7. Conceptual design study toward commercialization of FBR

A system configuration of Japanese commercial FBR, Japan Sodium-cooled Fast Reactor (referred to as “JSFR” hereafter), is depicted in Fig.6 with related innovative technologies.

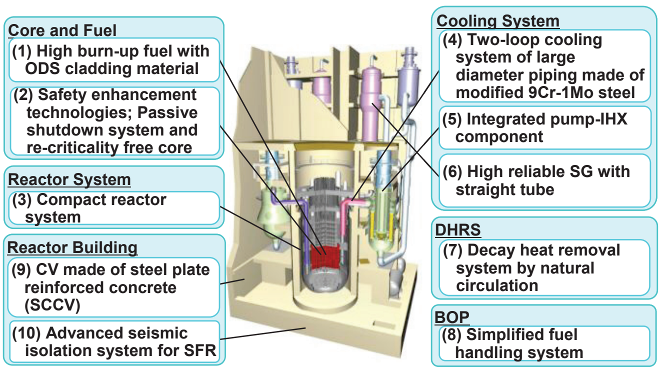


Fig.6 JSFR System Configuration and Related Innovative Technologies

The major design parameters for 1500 MWe plant of JSFR are listed in Table 1. The reactor inlet/outlet temperatures are 395℃/550℃. The plant efficiency is approximately 42%. MOX type fuel is used and the breeding ratio is approximately 1.1 or 1.2 so as to be flexible for the LWR-to-FBR cycle transition stage. A special effort has been made to meet the safety requirements, which satisfy no evacuation against the severe accident through the in-vessel retention.

Table 1 Major Design Specifications of JSFR

Items	*Specifications*
Output	3570MWt/1500MWe
Number of loops	2
Primary sodium	550/395 degree C 3.24×10^7kg/h/loop
Secondary sodium	520/335 degree C 2.70×10^7kg/h/loop
Main steam condition	497 degree C 19.2 MPa
Plant efficiency	Approx.42%
Fuel	TRU MOX
Breeding ratio	Break even(1.03)~1.2
Cycle length	26 Months or less 4 batches

8. SFR technology development in FaCT project

SFR technologies shown in Fig 6 employed in the large loop type reactor, JSFR, are focused and described below.

(1) High burn-up fuel with ODS cladding material;

The ODS(oxide dispersion strengthened) ferritic steel and PNC-FMS(ferritic martensitic steel) sub-assembly duct tube are selected to achieve the following values for the major targets of the JSFR core design:

1) 150 GWd/t for discharge average burnup for core fuel
2) 550 °C for reactor vessel outlet temperature
3) More than 24 months for operation cycle length
4) 1.2 for maximum breeding ratio

The maximum neutron dose and cladding temperature are $5x10^{23}n/cm^2$(E>0.1MeV, 250dpa(Fe)) and 700 °C which correspond to 150 GWd/t of average burnup and 550 °C of outlet temperature. Dimensional stability and high creep rupture strength are required for core materials of JFSR. .

(2) Safety enhancement technologies, passive shutdown system and re-criticality free core;

The Curie point electromagnet SASS consists of an electromagnet and an armature that are parts of its magnetic circuit containing a temperature-sensing alloy. The magnetic force is abruptly lost when the alloy is heated up to its Curie point by the heated coolant from the core. Then the armature de-latches at the detach surface and drop together with the control rod into the reactor core. The Curie point SASS is a simple structure and has flexibility of the detaching position. Re-criticality free core can enhance the molten fuel discharge through the inner duct in the fuel subassembly in case of CDAs, so that the severe energetics due to excursion could be avoided coupled with restricting core performance such as sodium void reactivity worth.

(3) Compact reactor system;

The reactor vessel accommodates a large core barrel. The slit Upper Internal Structure (UIS) allows for a fuel handling machine to access any fuel subassembly with a compacted single rotating plug. While the inlet and outlet piping come from the top of the reactor vessel, such piping arrangement contributes to enhance the structural integrity of the reactor vessel by suppressing local structural discontinuity like nozzles in its wall. Another feature is four ISI holes arranged at the roof deck from which a special ISI device (under sodium viewer) enters. This inspection hole extends from the top of the roof deck through the reactor core support skirt. Some inspection holes should be sufficient to access all the reactor core support skirt and the lower plenum region.

(4) Two-loop cooling system of large diameter piping made of high chromium;

The JSFR utilizes the advantage of the economy of scale with regard to component in the heat transport system by reduction of loop number. The number of main primary transport loop is set to two even for 1500 MWe power output. As a result, the heat transport system of the JSFR accompanies with a large volumetric flow rates in a large diameter piping system. The coolant velocities are 9.2 m/sec and 9.8 m/sec for the hot leg piping and the cold leg piping, respectively. Intensive experimental studies have been conducted to resolve resistance and fluctuating pressure of a large elbow in high Reynolds number.

The primary hot leg piping has been simplified by using a simple L-shaped piping. The shortened primary piping layout results in a compact plant configuration through a close arrangement of components, as well as a reduction of the amount of piping materials.

The design of the shortened piping layout and reduction of the loop number benefits from adopting high chromium ferritic steel, Mod.9Cr-1Mo, in place of an austenitic stainless steel, for the primary components and pipes, except the reactor vessel. The reason was that, thanks to the advances in steel production technology, ferritic steels can be used as the structural material of the primary sodium components and Mod.9Cr-1Mo pipes with confidence. In fact, Mod.9Cr-1Mo with improved creep strength and weldability has been developed for fossil power plant applications. The superior strength of Mod.9Cr-1Mo against thermal stresses comes from its low thermal expansion property and sufficient creep strength. Since the most important property required for JSFR structural materials is to accommodate the steady and transient thermal stresses, Mod.9Cr-1Mo possesses great potential as a JSFR structural material. The design of high chromium steel piping is modified by taking the Type-IV damage of the welding part into account.

(5) IHX with a Built-in Pump

The primary cooling system has been significantly simplified by adoption of an IHX with a built-in primary pump and elimination of middle leg piping. The baffle plates are installed to support the tube bundle as well as to improve heat exchange capability. Though the IHX with a built-in primary pump requires a larger tube sheet, an adoption of Mod.9Cr-1Mo ensures its structural integrity.

A critical issue in this component is the fretting wear of the heat transfer tubes by the baffle plate. For the tube integrity, vibrations transferred from the primary pump shaft to the tubes must be suppressed to an allowable limit. The experimental investigation is in progress to control the vibration of the tubes

(6)Higher reliable SG with straight tube;

It is desirable that a sodium heated SG of a commercialized SFR should minimize the possibility of sodium / water reaction, because the failure of plural heat transfer tubes by sodium / water reaction jets or reaction products significantly affects the availability of the plant. A number of kinds of tube design including double-wall tube, anti-wastage guard tube, are proposed to minimize the possibility of sodium-water reactions. An anti-wastage guard tube surrounding each tube could be strong enough to suppress the tube failure propagation by target wastage from an initial failure tube.

(7) Decay heat removal system by natural circulation;

The JSFR adopts a combination of one loop of DRACS and two loops of PRACS. PRACS are located in the upper plenum of IHXs. Heat exchangers of DRACS are arranged in the reactor vessel. These DHRSs can be operated under fully passive conditions, which mean that, without pumps and blowers, it is required only to activate the DC-power-operated dampers of the air coolers. The damper system has redundancy so that it does not lose its function even considering the single-failure criterion. In addition, diversity is taken into account in the mechanical design of the dampers between DRACS and PRACS. JSFR is suitable for natural circulation cooling due to its simple and short piping connection and due to the lower pressure loss of the core design, as well as the sufficient height difference between the core and the heat exchangers. Since both DRACS and PRACS have a sodium-sodium heat exchanger inside the primary heat transport system, they are not affected by the abnormal conditions initiated in the secondary heat transport system and the steam-water systems. Regarding the DRACS, the primary sodium flow consists of natural circulation in primary loops and also the gap flow between fuel subassemblies.

(8) Simplified fuel handling system(FHS);

The FHS consist of an in-vessel fuel handling machine, a fuel transfer pot with two fuel subassembly positions, an external fuel storage tank, an ex-vessel fuel transfer machine, a spent fuel storage water pool, spent fuel cleaning facilities and a new fuel handling facility. A full-scale mockup test results show that normal operations were performed without any problem, required positioning accuracy and operation speed was achieved and the positioning can be precisely controlled. The test results also show that when there was malfunction, the FHM was basically removed from the reactor vessel to repair.

(9) Steel plate reinforced Concrete Containment Vessel (SCCV);

Steel plate reinforced concrete structure is composed of steel plates assembled at a factory which contribute to improve the quality of the structure. As for the construction method, the modular structure is planned where large-sized box units are constructed in a factory, and conveyed to the site by ships and dollies. The modular structure unit construction method is expected to reduce the construction term. Thus, the SCCV has a potential to shorten the construction period with a modular structure unit construction method aiming at achieving a high level of economic performance. Experimental studies are being carried out to understand the basic thermal and/or mechanical behavior of components consisting in SCCV in case of assuming sodium leak.

(10) Advanced seismic isolation system for SFR;

The design seismic loading became more severe than ever since The Niigata-ken Chuetsu-oki Earthquake in 2007. Seismic isolation system was optimized by considering the natural frequency of the primary components. The advanced seismic isolation system functions horizontally and consists of a combination of laminated rubber bearings thicker than existing ones and the oil dampers. The feasibility of the thicker laminated rubber bearings was confirmed by a basic characteristic test with 1/8 reduced scale model.

9. Conclusion

1. The five development targets have been set to cope with the future diverse needs, where the efficient utilization of resources and the reduction of environmental burden are both crucial issues for the sustainable energy source to be harmonized with the environment.
2. Monju has, as the Japanese prototype reactor for the purpose of FBR commercialization, an important mission to provide indispensable technical information for design, operation and maintenance of demonstration and commercialized FBRs.
3. FaCT project has steadily advanced a large size loop-type sodium-cooled reactor JSFR with mixed uranium-plutonium oxide fuel, supported by a fuel cycle based upon advanced aqueous processing under the FaCT project. The design of JSFR and its R&D of innovative technologies identified as 10 issues are now in progress.

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